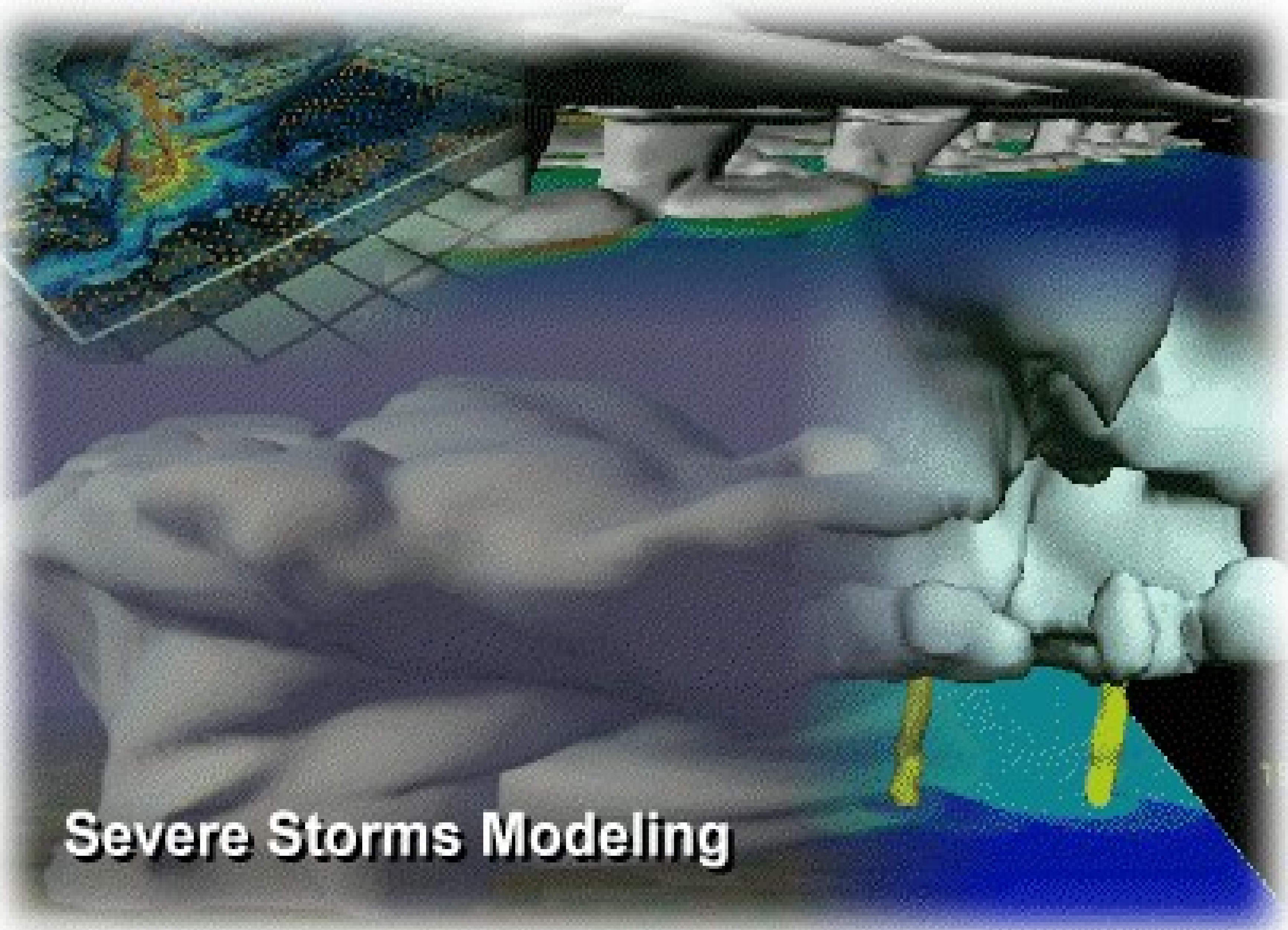

Severe Storms Modeling

Supercells

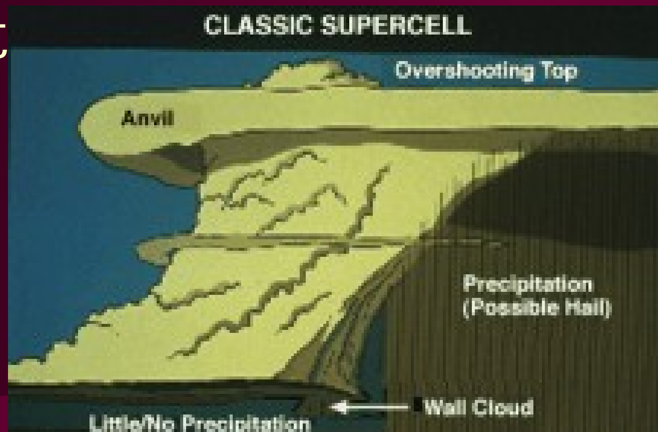
Introduction

Supercells are long-lived thunderstorms which exhibit quasi-steady structure including a rotating updraft. These storms generally produce severe weather including heavy winds, large hail, heavy rainfall, and occasionally tornadoes. In fact it is these supercells that produce the st

With the danger that supercells pose, it is wise to learn more about the nature of their origin and evolution. By discovering how supercell behavior is related to the surrounding environment, meteorologists can help predict when and where such storms will actually occur -- with the ultimate goal of saving lives. While real supercells like the one in the photograph above continue to occur, computer model visualizations like the one below are being used to advance our understanding and prediction of th

Supercell Structure

Supercells have a common structure, as can be seen by the left diagram below. Computer model visualizations (below right



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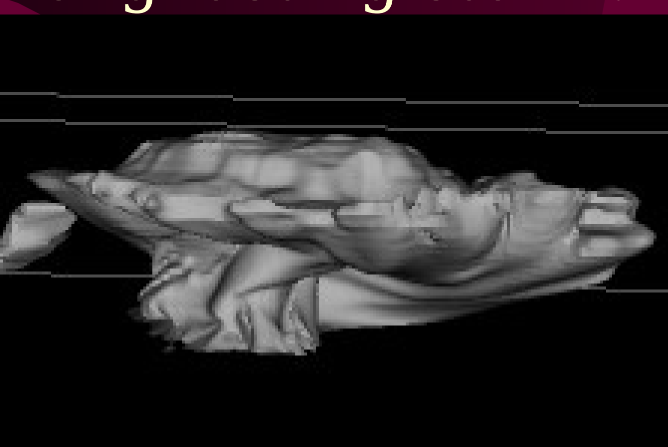
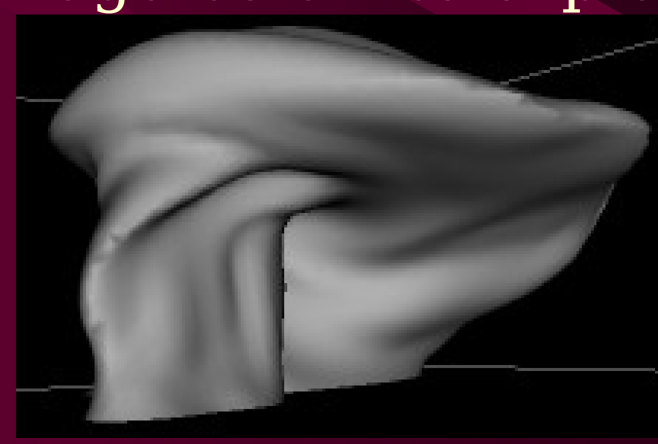
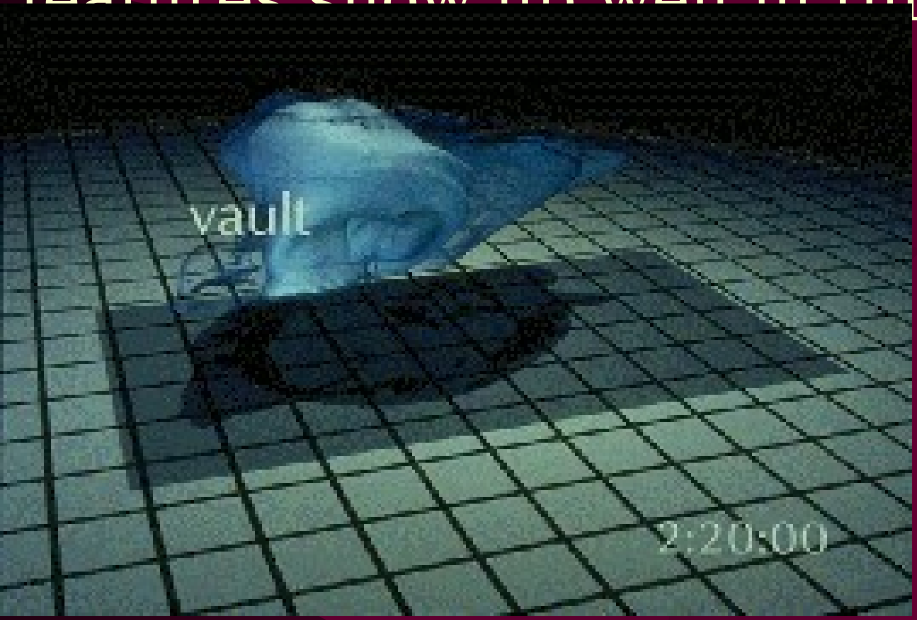
Supercells are characteristically tall storms -- reaching way up into the stratosphere. The main updraft and downdraft mutually support one another leading to a long lasting storm. Click on the image below to explore a



ough VRML.

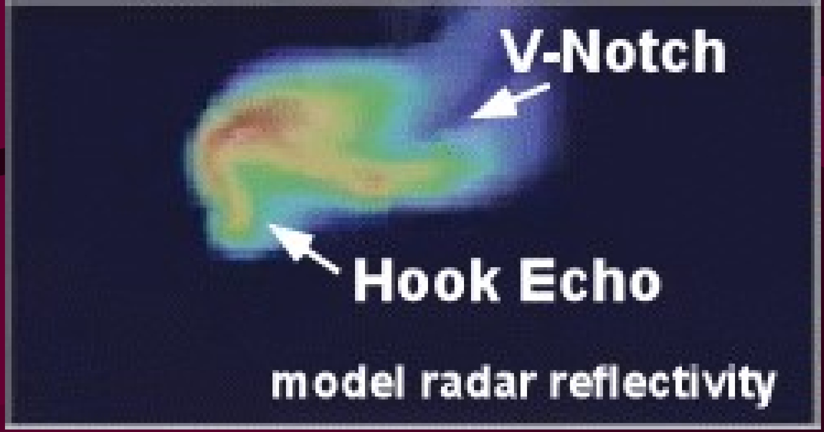


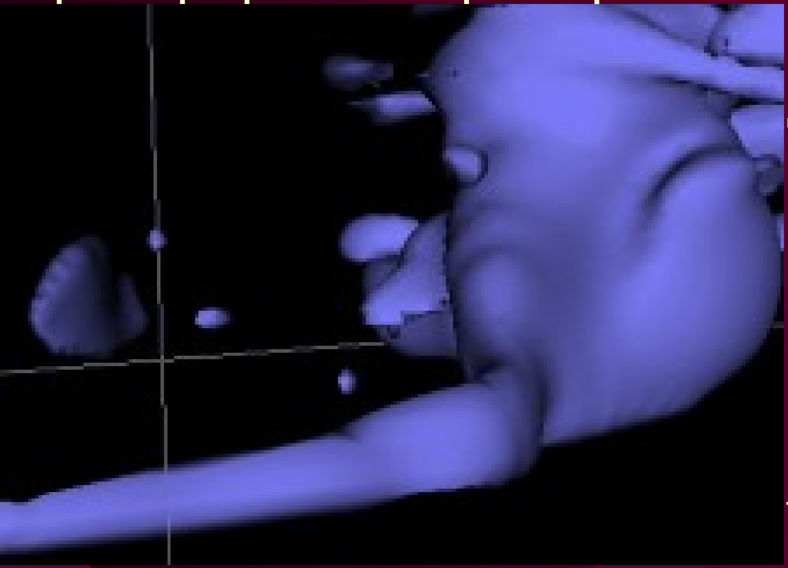
Often, if you can see the whole storm, you can see a large dome above the central updraft and a broad, flat region covering the entire storm and extending downwind of the updraft. This is called the anvil, and both features show up well in this



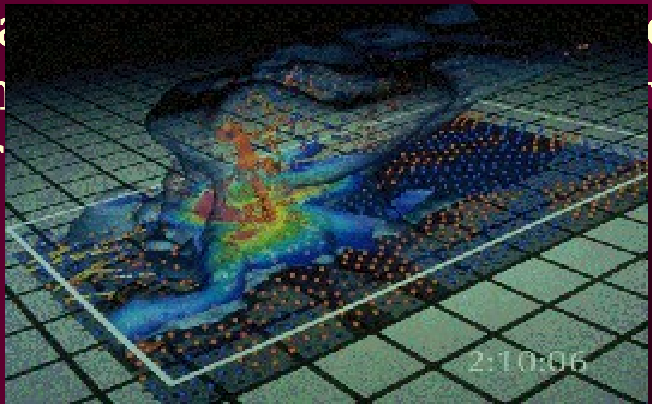
Another characteristic observable in both models and in nature is the large cloud free area above the base of the updraft known as the vault or Weak Echo Region. Rain and possibly hail fall to the ground outside this region, leaving the vault

In some supercells, one can sometimes observe both a v-notch and a hook echo. In this modeled radar image, both are evident. A hook echo is a strong signal that a supercell thunderstorm is about to or





Some supercell thunderstorms also possess a clearly visible flanking line. The flanking line separates cool storm outflow from warm moist storm inflow and sits above the gust front. New storms form along the flanking line as the moist inflow air rises as it approaches the cool surface air. In this VRML environment, the blue body represents a … d developmen … very evident (for



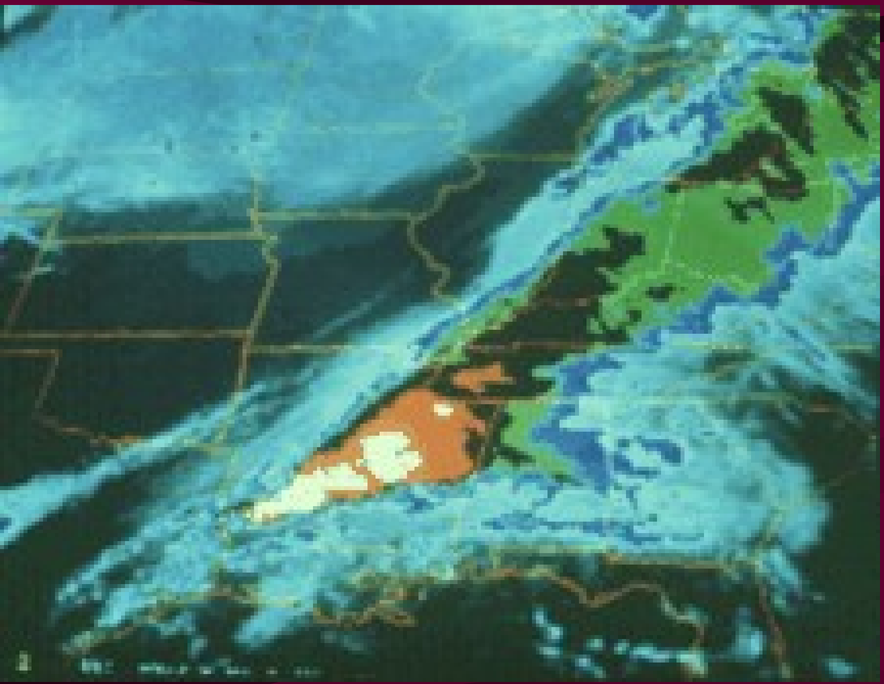
Weightless particles are used to trace the air motion within a supercell. Blue balls are sinking and orange balls are rising

Supercells and Tornadoes

The strongest and most damaging tornadoes from within supercells. This is one of the primary reasons why researchers strive to understand them better. They want to be able to pr more accurately.

Computer models can now produce the general behavior of tornadoes like the one above on the right. Weightless tracer particles are used to define the tornado's flow. However, determining which supercells will produce tornadoes remains a challenging task that is still under

Convective Lines



Lines of convective cells can also produce severe weather and substantial damage.

Tornadic supercell thunderstorms can develop in squall lines. Tornadoes (non-supercell) can also appear in developing lines in which the parent storms exhibit little rotation.

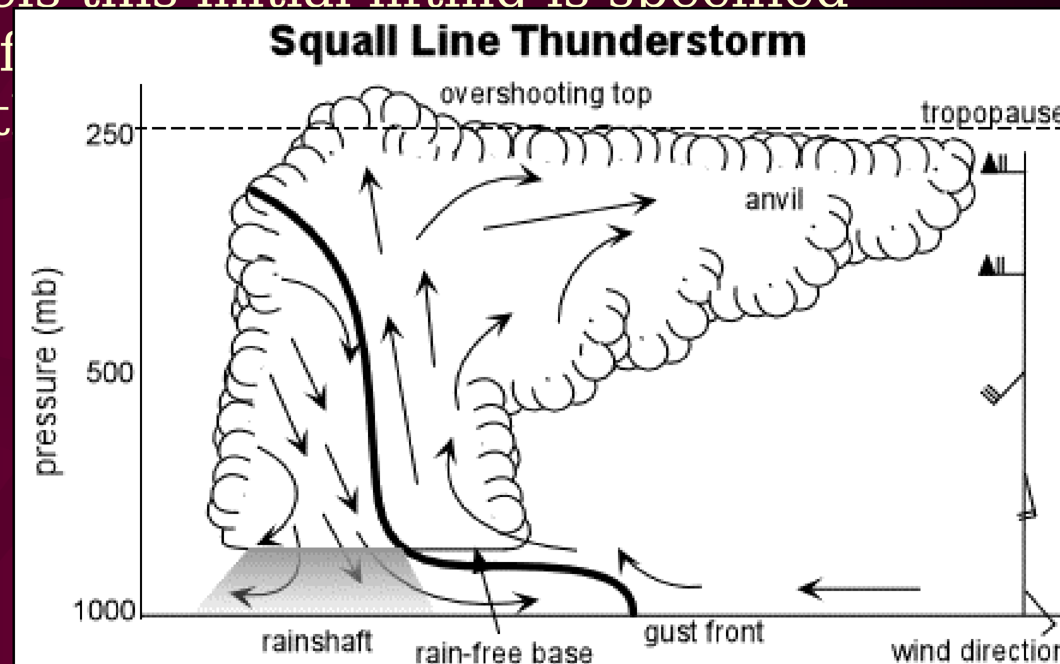
Squall Lines

Squall lines generally form along or ahead of cold fronts and drylines and can produce severe weather in the form of heavy rainfall, strong winds, large hail, and frequent lightning.

Squall lines can extend to hundreds of miles in length, simultaneously affecting several states at a time. They also can travel quickly -- at speeds up to 60 mph.

Squall lines typically form in unstable atmospheric environments in which low-level air can rise unaided after being initially lifted (e.g., by a front) to the point where condensation of water vapor occurs. Heat is released during condensation, resulting in the rising air becoming lighter than nearby air at the same height. This leads to an increase in the speed of the rising air which sometimes reaches speeds above 30 mph. In models this initial lifting is specified through an idealization of the f
lifting mechanism or through t
information.

The gust front is located along the line where these winds meet -- which extends from the surface well up into the the storm.

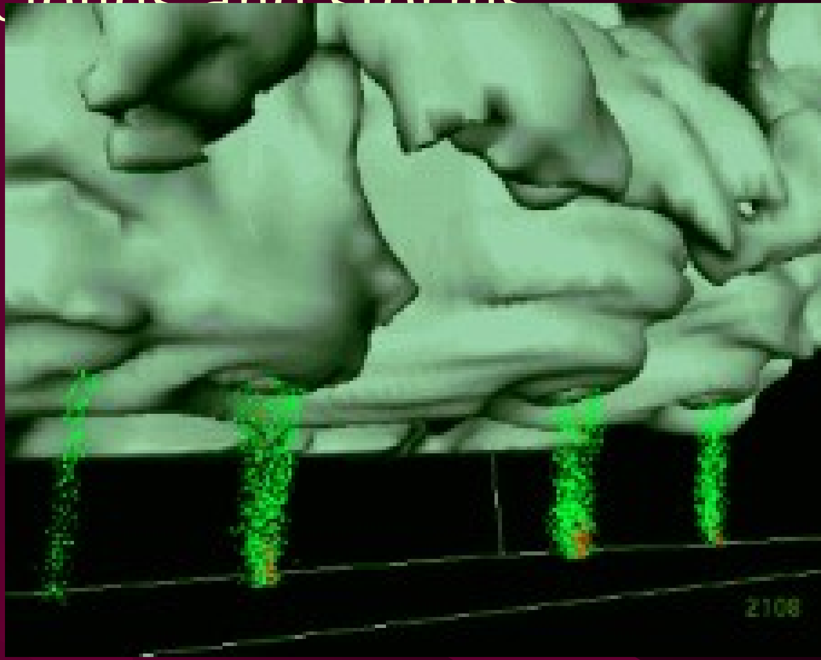


The schematic above is a depiction of the structure of a well-formed squall line. Such schematics are often a key result of a scientific investigation and can be based on observations, model and/or theory. They help communicate some of the key features in a simple and concise way. Note the similarity of the schematic to features in

Nonsupercell Tornadoes

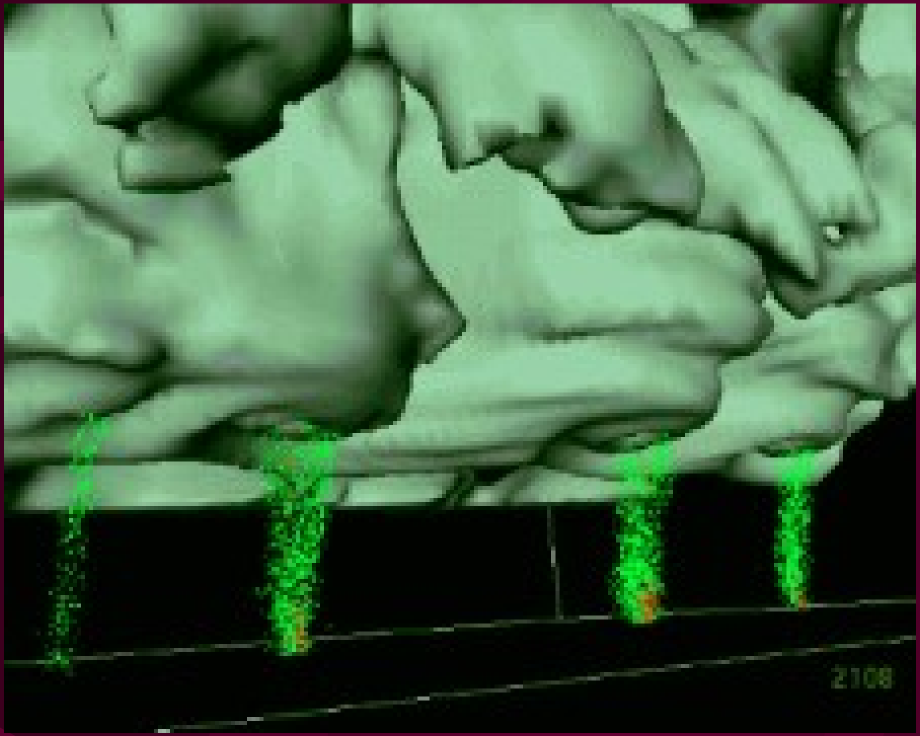
tornadoes produced from non-rotating storms

Even though supercell thunderstorms are responsible for the biggest and deadliest tornadoes, a significant number of tornadoes form under nonsupercell clouds and storms.



The left photograph below shows such an event. Notice that there are three tornadoes (there were actually five, but only three are pictured) that exist simultaneously. Modeling efforts to reproduce events like this have been successful as seen by the illustration below (right). Weightless tracer particles define the tornadoes.

These nonsupercell tornadoes (NST) are normally short-lived and weak, but from time to time can become strong enough to damage property and kill people. Because of this, researchers are investigating how a rotating entity like a tornado can be produced beneath clouds with non-rotating updrafts.



Severe Storms Forecasting

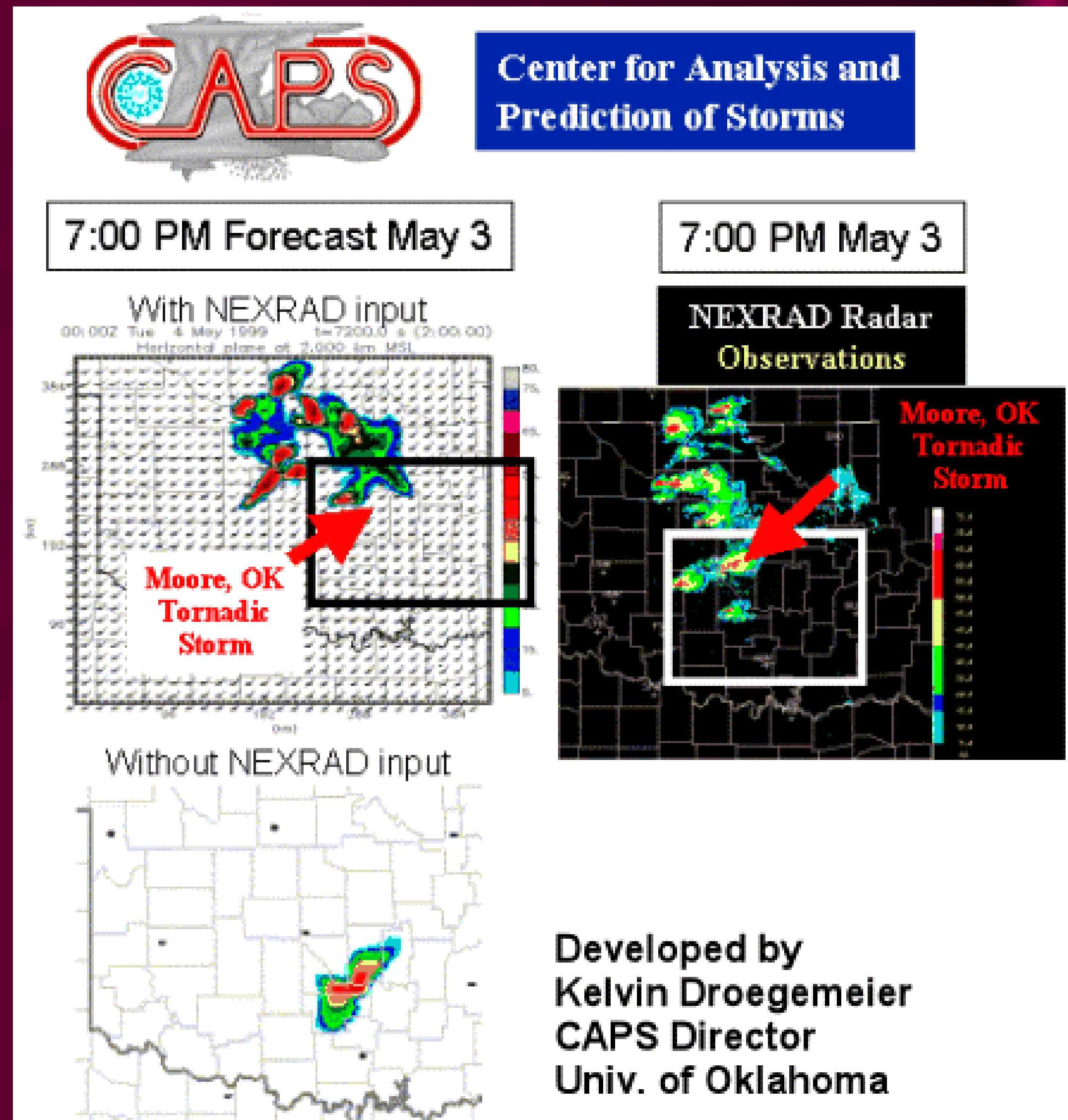
anticipating the danger

Severe storms modelers have performed many simulations over the years with the intention of helping to make more accurate forecasts.

Modelers can alter the environment that a storm starts and evolves in. Changes in storm behavior can then be assessed. An important characteristic of the atmospheric environment is vertical wind shear, a measure of the change in horizontal wind speed and direction with height. Researchers have found that different vertical distributions of wind speed and direction can make the difference between whether a storm becomes a harmless shower or a tornado producing supercell seen below. The

As a result of all of these studies, the research community has provided forecasters with information on the relationship between the storm environment and the type and behavior of storms that could possibly develop.

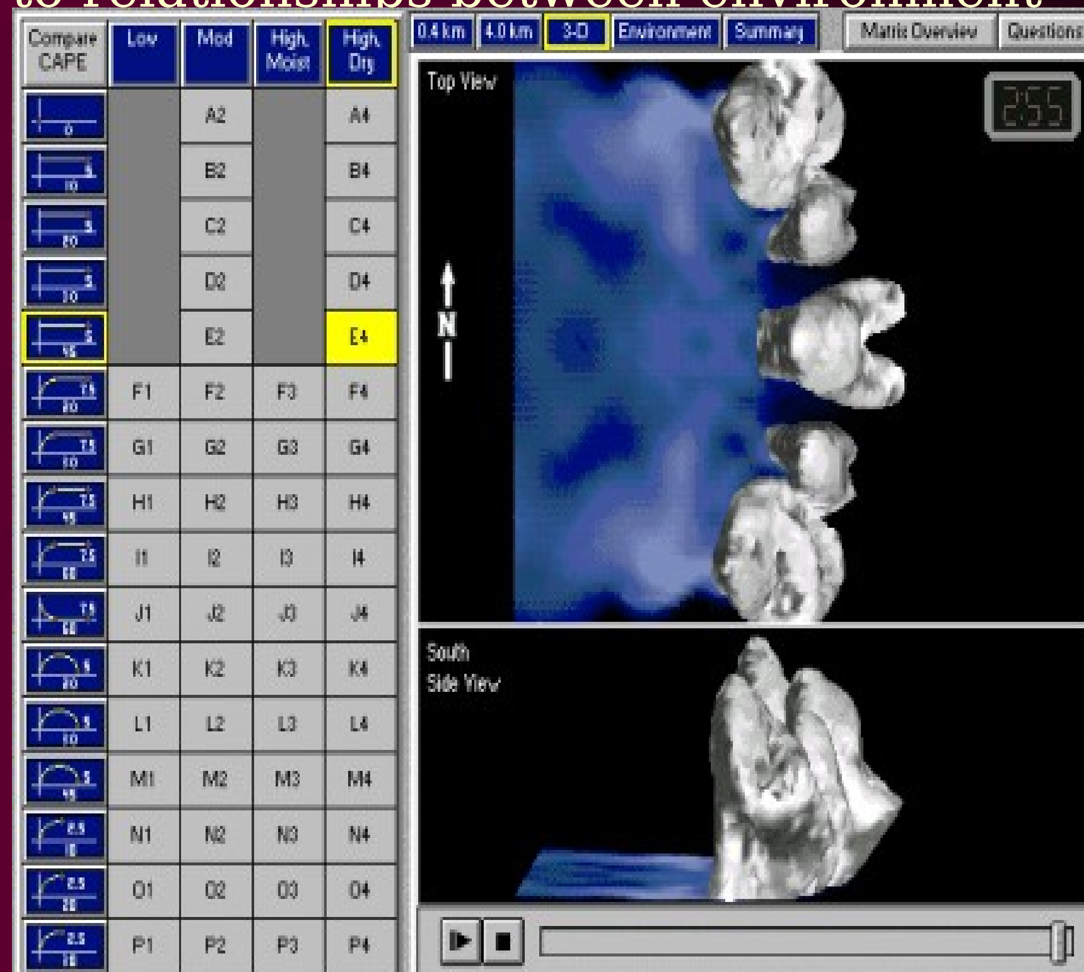
In addition, severe storm modelers have begun using high-resolution forecast models to predict severe weather. These models are initialized with a wide variety of observational data that reflect the character of the current atmosphere. Data includes surface and balloon data, aircraft data, and recently Doppler (NEXRAD) radar data. The benefits of this new direction in severe storm forecasting has already been demonstrated. Below is a forecast for the devastating tornadic storm in Oklahoma on May 3rd, 1999. The improvement in predicted storm



Forecast Matrix

developing a environment to storm relationship

Severe storm modeling has provided forecasters with a useful learning tool -- forecast (or convective) matrices. These matrices serve to practically condense years of modeling research results and give forecasters quick access to relationships between environment and storm type.



A forecast matrix is built by making many simulations using different combinations of wind shear and CAPE that are representative of actual storm environments. Different storm behavior is observed in these different environments. The matrix shows these results to the forecaster in the form of low level and mid level radar signatures, cloud visualizations, wind patterns, and sometimes, a brief explanation. For example, below is a 3-D view of thunderstorms that develop in a

Forecasters always have estimates of wind shear and CAPE. With these, they can refer to the matrix and can get a first estimation about the potential for any developing storm to be severe.

Unfortunately, environments can change very quickly and once a storm develops, it can change its own environment. This means that the matrix is best used as a guide, and other factors -- observations, forecast models, spotters, and experience -- are vitally important.

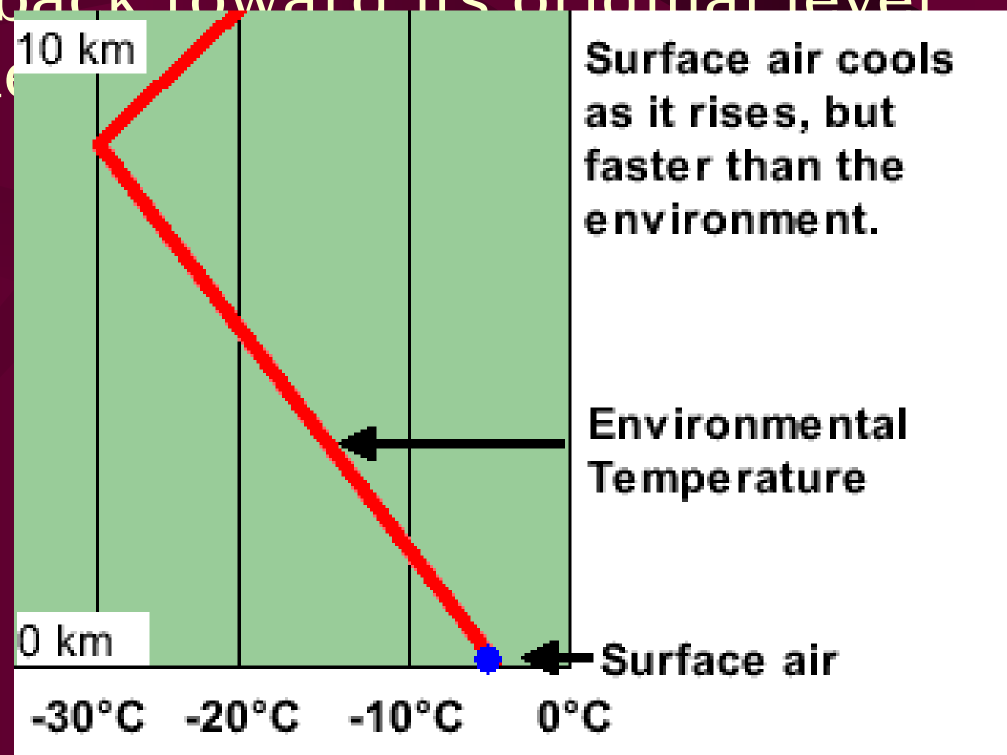
Stabili ty

Storms developing in one environment can be different in character than those developing in another. Modelers can alter the stability of the atmosphere in which they simulate storms by changing the vertical distribution of temperature and moisture.

Thunderstorms develop when surface and low level air is allowed to rise without restriction into the upper troposphere. If air rises in an environment without restriction, the environment is said to be unstable. This means that stability is simply the resistance the atmosphere imposes on rising (or sinking) air.

Stable Environments

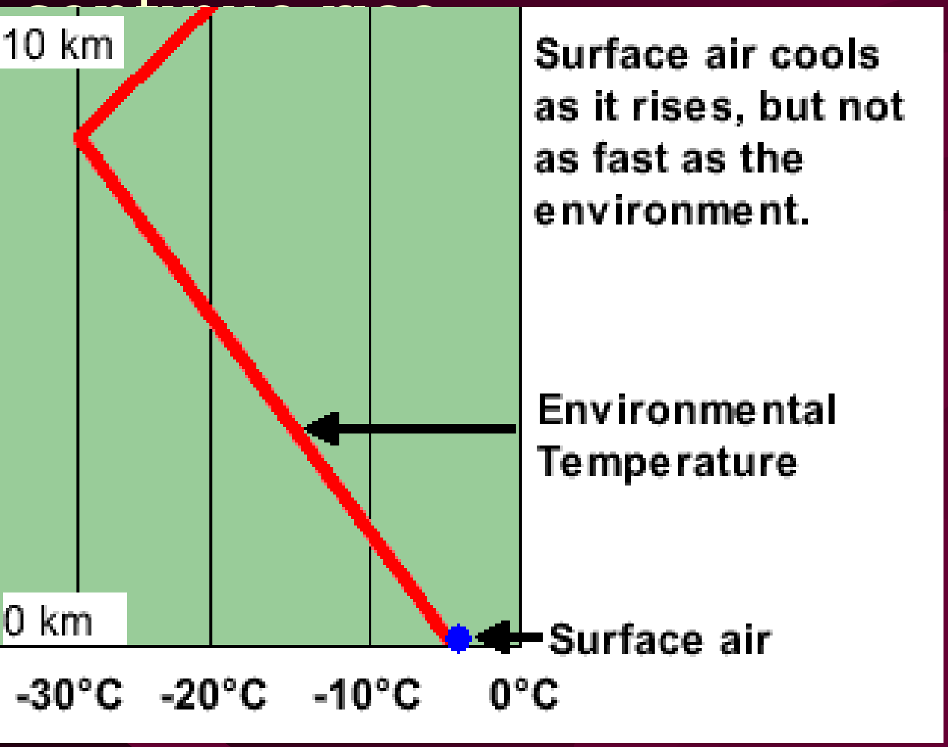
Air temperature in the atmosphere generally decreases with height. However, when low level air rises, it cools at a rate that is often different from the air's surrounding environment. If, as it rises, the low level air becomes colder than its environment, it would be more dense than the environment and fall back toward its original level. This is a **stable** environme



The only way air can rise in a stable environment is for a mechanical force such as a front to lift it.

Unstable Environments

If, however, the rising air cools at a slower rate than the surrounding atmosphere, it will be warmer (and less dense) than its surroundings. Here, the rising air would continue to rise.



The larger the temperature difference between the rising air and the environment, the more buoyant the rising air is. The more buoyant the air is, the faster it can rise, and the more severe the thunderstorm can become.

Sometimes, the environment is stable near the ground and must be forced to rise into unstable air by a front or other mechanism.

Wind Shear

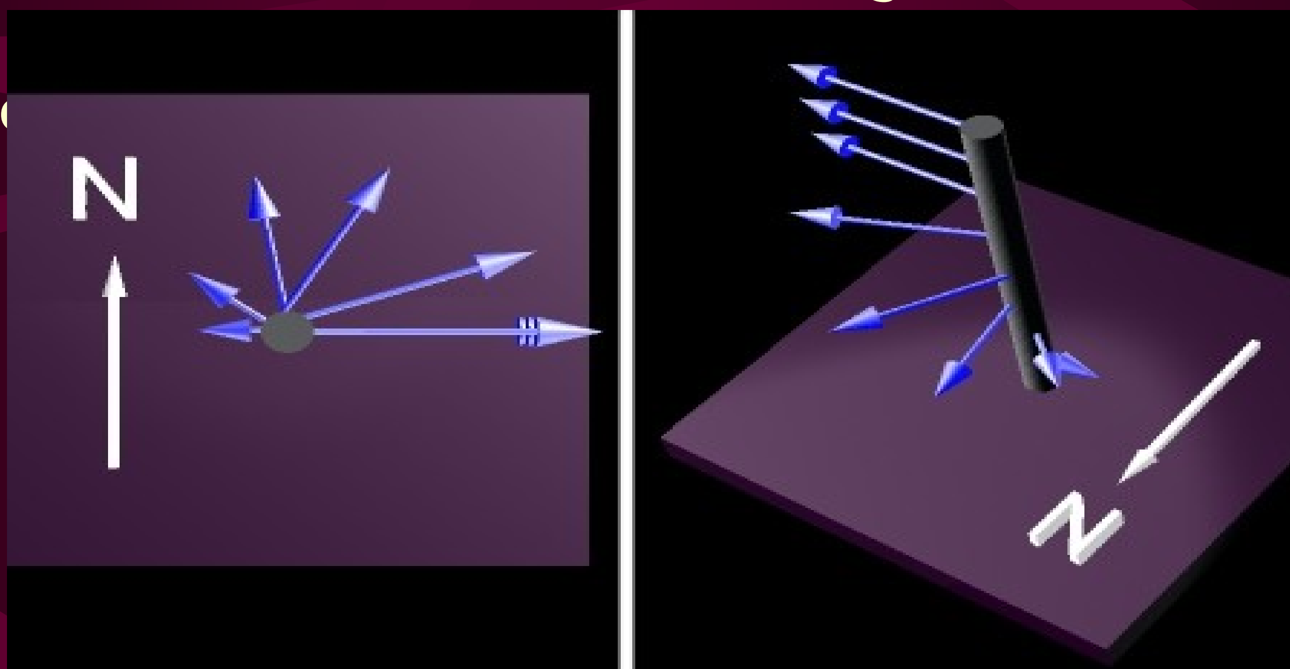
The environmental wind field is also very important in determining what type of a thunderstorm could develop. Severe weather usually occurs when the change in horizontal winds (wind shear) is significant. This includes the change in wind direction (directional shear) or speed (speed shear).

Speed Shear

In speed shear, the wind increases in speed from the surface to the upper levels, as shown in this diagram by the arrows. This vertical shear creates horizontal rotation which can best be visualized by placing a paddle wheel in the environment. Besides the rotation, the change in wind speed with height lets the updraft separate from the downdraft, allowing the storm to

Directional Shear

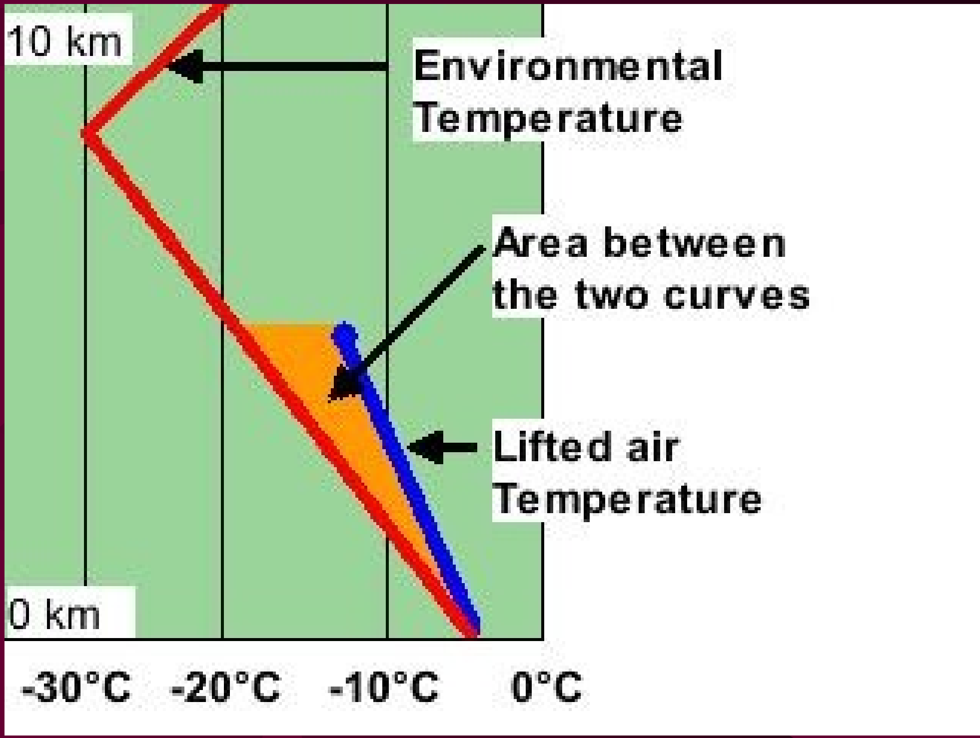
Directional shear refers to a change in the direction of the wind with height. Notice in this image there is both speed and directional shear as both the angle and the length of the wind vectors are changing with height. Two viewpoints are shown in the following figure. The length of the arrows represents the wind speed. The arrows point in the direction that the wind is blowing and are located at different heights in the column of air shown. from one level to an



Modelers run experiments with storms developing in different amounts of wind shear. Differing amounts of wind shear can determine whether a storm remains small or becomes a supercell.

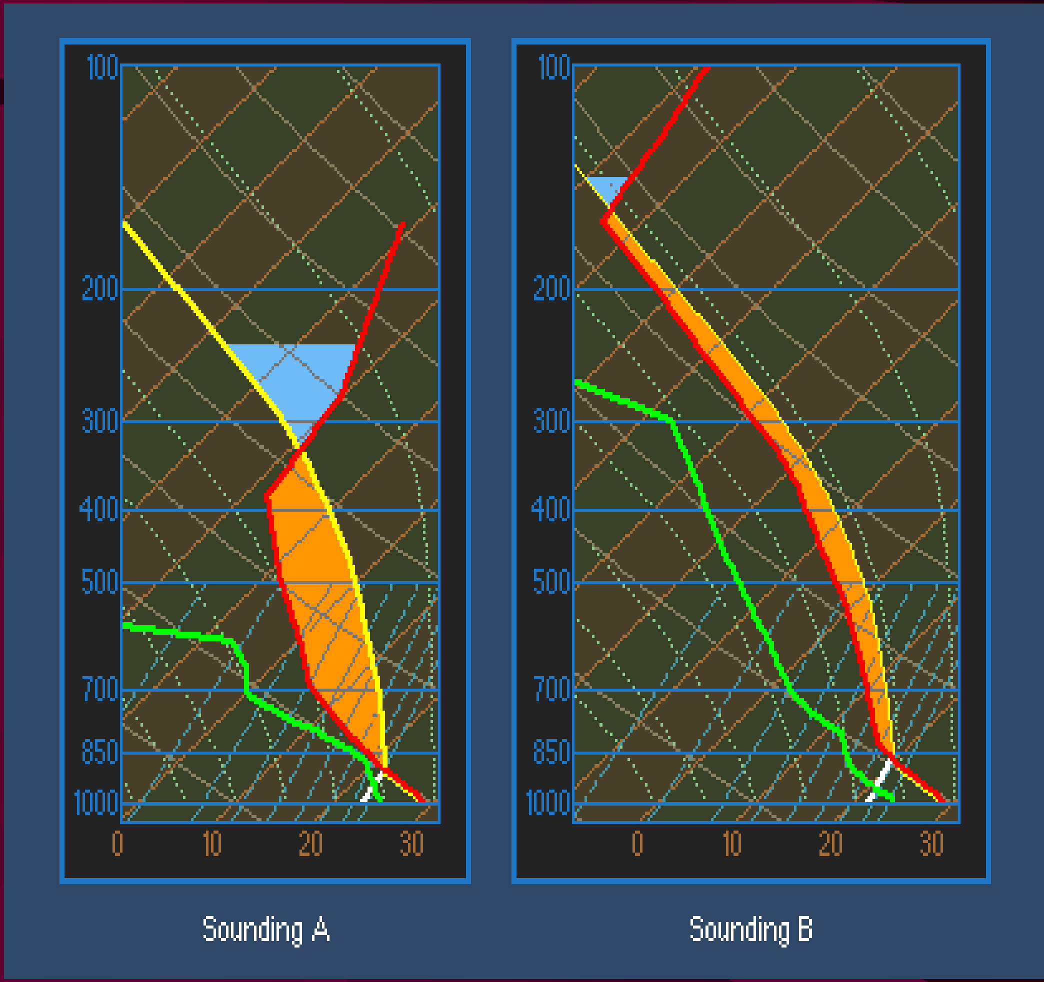
CAPE

In an unstable environment, the temperature of rising air can be traced and compared to the vertical profile of the environmental temperature.



The area between these two lines is representative of the available energy a storm could use to grow. This energy is call CAPE (Convective Available Potential Energy) and comes from the energy released when water condenses.

There are two aspects of CAPE that meteorologists look at when diagnosing severe storm potential -- the size and the distribution of the orange area. The size (or magnitude) of CAPE is important as it describes the potential strength (e.g. updraft speeds) within storms. However the distribution of CAPE is just as important. This is because the same CAPE (orange area) could come from an environment with a large temperature difference over a shallow level or from a smaller temperature difference over a deeper level. The diagram below shows this. The orange areas (and therefore CAPEs) are identical.



Notice how in the sounding A, the difference in temperature between the environment and the rising air is much greater than in sounding B. This means that the rising air in sounding A is more buoyant with respect to its environment than that of the air rising in

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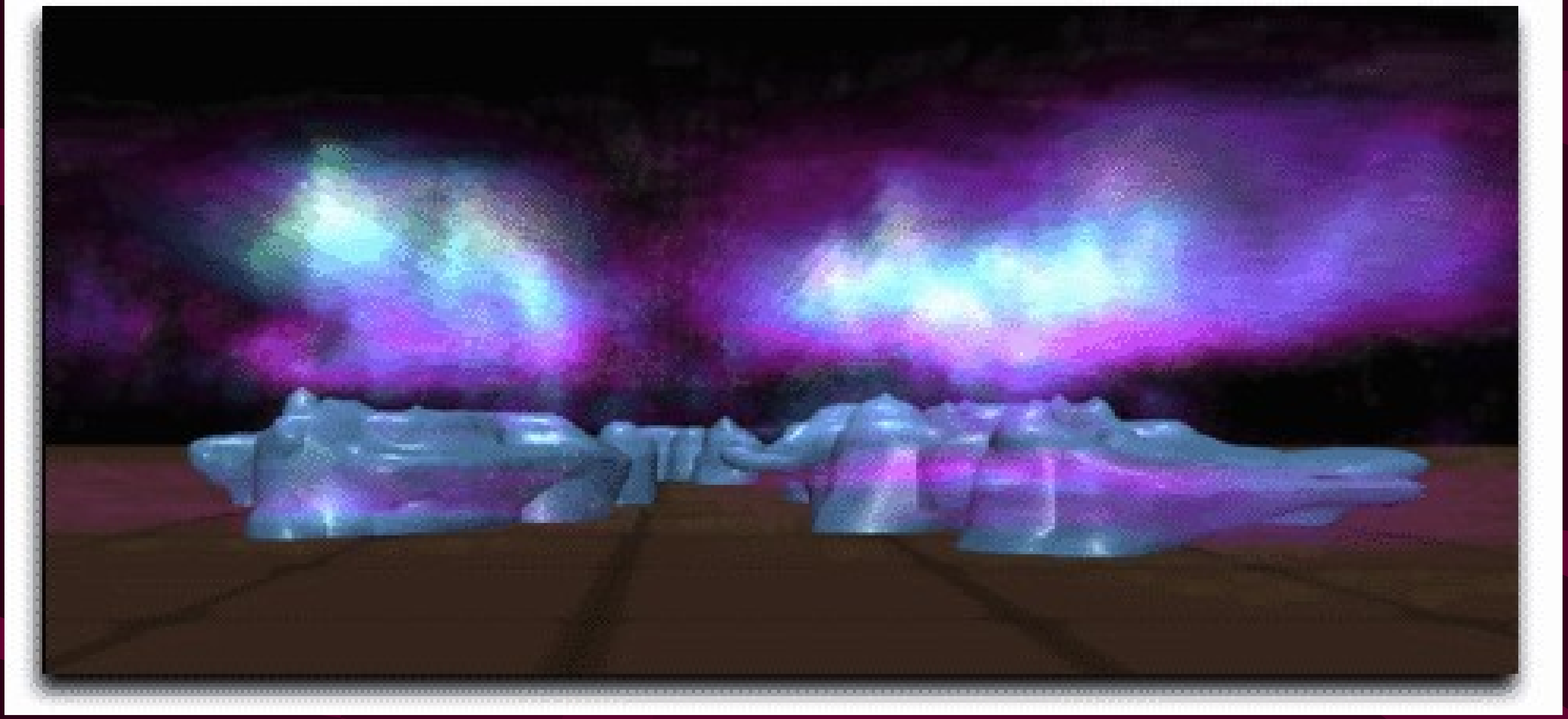
On April 3 and 4, 1974, lines of thunderstorms east of the Great Plains unleashed 148 tornadoes. This outbreak was the largest and most violent in U.S. history. Winds exceeded 261 miles per hour. Hail pummeled young crops and shattered glass. Three hundred fifteen people in 11 states were killed; 6,172 were injured. Hardest hit was Xenia, OH, where a tornado cut a half-mile wide swath through the center of town. Winds tossed a school bus through the wall of the high school gymnasium and onto the stage only minutes after students rehearsing a spring musical had fled.

Droegemeier, now a professor of meteorology and director of the Center for Analysis and Prediction of Storms at the University of Oklahoma, wants to stretch severe storm warning time from minutes to hours. And he wants to predict where a storm will strike to within a few miles. "We want to be able to say that from 3:30 to 3:45 this afternoon a line of thunderstorms will pass over the airport with 50

Such pinpoint predictions are still years away. But in the quest to refine forecasts from the nation to the neighborhood, Droegemeier's team is leading the pack. In January they unveiled a new version of their Advanced Regional Prediction System (ARPS) during the annual meeting of the American Meteorological Society in Dallas, TX. Using all 128 processors of an SGI CRAY Origin2000 at NCSA, Droegemeier's team generated daily real-time forecasts at resolutions of 32 km, 9 km, and 3 km. A 3-km resolution is equivalent to predicting the weather at points 12 city blocks apart.

"Droegemeier's model will provide more information about an impending storm," says Mike Fritsch, a professor of meteorology at Penn State University. "It will give you more accurate estimates of the timing, location, and properties of a given storm system; for example, whether or not there are going to be thunderstorms and if they are likely to be severe. In other words, it is a sharper window on weather. That's a substantial step

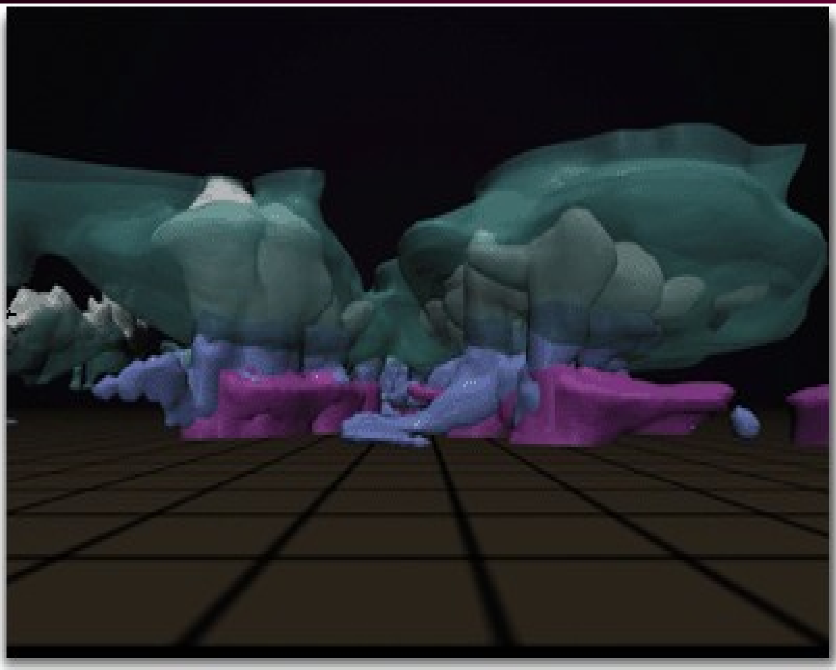


On June 16, 1997, a severe band of thunderstorms swept over the Great Plains. Meteorologists at the Center for Analysis and Prediction of Storms at the University of Oklahoma predicted the evolution of these storms by incorporating data from several sources including Doppler radar into their storm prediction model. The data from their forecasts were used by NCSA's David Bock to generate the image seen on the cover. Ice, snow, and cloud moisture variables are combined and rendered

Droegemeier has been simulating severe storms for 15 years, first as a graduate student working with Robert Wilhelmson at the University of Illinois at Urbana-Champaign (and now also at NCSA), where he reproduced storms to understand how they formed, and later as a professor at the University of Oklahoma, where he built forecasting models and studies of the dynamics and predictability of storms. In 1989, he and an Oklahoma colleague, Doug Lilly, were awarded an 11-year grant from the National Science Foundation to establish a Science and Technology Center that would go beyond predicting the conditions favorable to the formation of severe storms to predicting when and where a storm will strike. The result was ARPS.

ARPS was designed for all types of local high-impact weather but has been tested most extensively on the so-called supercell storms: the towering thunderstorms that darken skies in the spring and can unleash within their one- to two-hour lifespans the energy equivalent to several atomic bombs. "Supercell storms are among the most menacing weather events," says Droegemeier, "and are difficult to predict with computer models."

Why? Meteorologists have known since the 1950s that thunderstorms form where cold, dry air overlies warm, moist air. Some slight instability shoves the warm air upwards, triggering a cycle of updrafts and downdrafts that erupt into storms. A hitch has been identifying these triggers. A mountain range will do it, but so will small differences in vegetation and soil moisture. Then there's predicting the motion and decay of the storms once they form.



These images of a thunderstorm on June 16, 1997, were generated at NCSA with forecast data from the Center for Analysis and Prediction of Storms at the University of Oklahoma. In the top image, rain, ice, snow, and cloud were rendered as isosurfaces so that the boundary of each moisture variable was easy to distinguish. Rain is purple, ice is gray, snow is a translucent teal, and clouds are blue. In the smaller image, only rain was rendered as an isosurface. The other variables were

ased

What sets ARPS apart is that it continually ingests data fine enough to capture essential storm details. Just as a checkbook's ending balance cannot be right if the starting balance is wrong, a forecast cannot be right if it starts with incomplete data. The starting balance for ARPS comes from geostationary satellites, ground-based observing systems, and the National Weather Services' new NEXRAD Doppler radar network.

Generating 10 daily forecasts for 7 days straight required:

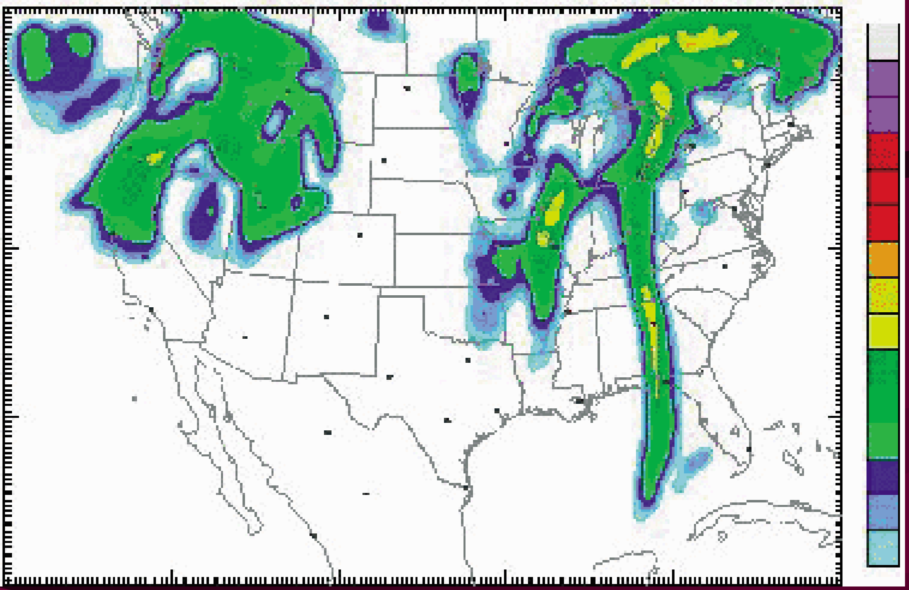
- 2 gigabytes of observational data per forecast
- 2 million computational cells
- 1 million billion floating point operations
- 6 billion floating point operations per second

The forecasts were generated six times faster than real time -- that is, a one-hour forecast took 10

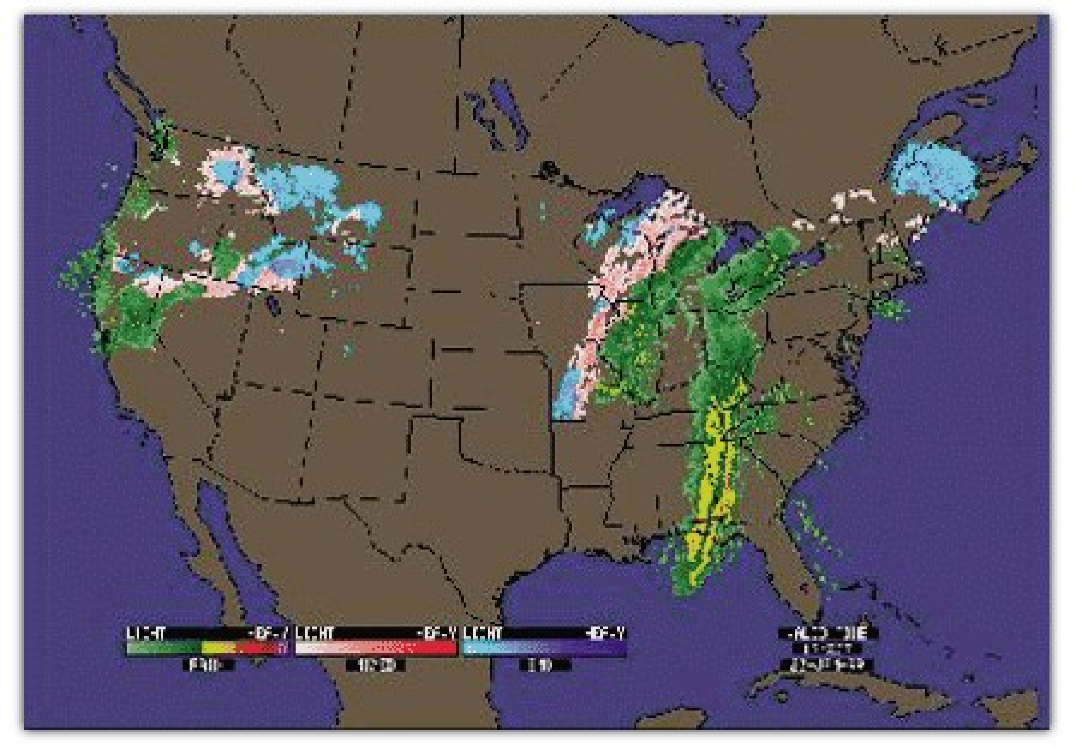
Distinctive, with a globe perched atop a scaffoldlike structure, Doppler radars record wind speed and direction -- essential for predicting how a storm will form and evolve -- every five minutes at 1-km spatial intervals throughout the 11 to 13 layers of the troposphere -- the 10 vertical miles that constitute the weather-producing portion of the atmosphere. The Weather Service installed the last of its 123 Doppler radars last summer, which are being tied in with another 23 Doppler radars at sites operated by the Department of Defense and the Federal Aviation Administration. The NEXRAD data are usually "thinned" to four layers before being transmitted to Weather Service headquarters in Silver

Droegemeier's center, however, receives the full-volume NEXRAD datastream from eight radars in the southern Great Plains through a project funded by the Oklahoma State Regents for Higher Education that uses an advanced statewide network called OneNet. The center's researchers were the first to devise a means for using these data in real time for storm predictions, and now ARPS runs daily. The center's researchers also developed techniques for retrieving the 3D dynamics of a storm from 1D data. Doppler radar measures wind motion parallel to the radar beam, which is only one dimension of the wind. "Think of this radial wind component as north-south," explains Droegemeier. "You also need east-west and up-down wind." Weather prediction models calculate about a dozen other variables, such as temperature, pressure, and moisture fields.

The computational demands of digesting 1.5 gigabytes of Doppler data and then calculating these variables explains why Droegemeier's team needed all 128 nodes of NCSA's Origin2000 to run their model in real time. Earlier versions of ARPS were run on different supercomputers at the Pittsburgh Supercomputing Center.



ARPS uses fine-scale NEXRAD Doppler radar data and other observations to generate forecasts at three resolutions: 32-km intervals for national forecasts; 9 km for multistate regions (1782 km x 1782 km); and 3 km for local areas (594 km x 594 km). Above is a 24-hour ARPS forecast for January 23, 1999, at 6 a.m. (CST). Below is the actual radar observation.



"The future of forecasting is local, local, local," says Henry Margusity, a meteorologist and sales manager for AccuWeather, a private weather service that supplies forecasts to some 10,000 clients. "People want the weather for their backyard."

The potential for eliminating local weather-related surprises is what makes ARPS an exciting endeavor that is attracting the attention of commercial and private enterprises. The South Korean National Government recently adopted ARPS as its official severe storms model. Since 1996 American Airlines has invested more than $1 million, a decision made after two massive hail storms in one week at the Dallas-Ft. Worth Metroplex, American's main hub, cost them millions in damaged airplanes and cancelled or diverted flights.

ARPS is also a gamble because it raises people's expectations about what is possible even though the potential for error is great. As Droegemeier likes to point out, a local prediction by ARPS that is off by 20 miles may well be a bust even though that same precision in a